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# 1-Watt Composite-slab Er:YAG Laser

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A diode-side-pumped discrete-optic $Er^{3+}$:YAG laser employs pump-light coupling through a sapphire plate diffusion-bonded to the laser slab, giving reduced thermal lensing and exceptional beam quality ($M^2 \sim 1.3$.) The novel architecture is also applicable to other side-pumped lasers.

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The $Er^{3+}$ laser has recently been investigated rather intensively with the goal of improving its efficiency[1 - 3] and understanding the complex level kinetics[3,4] that allow quasi-CW operation in a variety of oxide[5] and fluoride[6] hosts. Near-Watt-level operation has been demonstrated, mainly with end-pumped[1 - 3, 5] and monolithic[1, 5] designs that inherently afford excellent spatial overlap between the tightly-focused pump and resonated beams. Unfortunately, limited diode pump brightness hampers scaling to higher power levels in such schemes.

To sidestep this diode brightness limitation, we developed a side-pumped laser[7] (based on a design introduced by Bernard[8]) compatible with LLNL-developed high-brightness laser diode array packages. Characterization of this laser showed that thermal focusing in the laser slab limited the obtainable average power and beam quality. Also, a substantial increase in laser efficiency could be achieved by lowering the temperature of the Er:YAG crystal.

Evidently much can be gained with improved cooling techniques that (a) reduce the temperature in the gain region and (b) reduce thermal lensing. Our new "composite" design (Figure 1) has the Er:YAG crystal bonded to a sapphire plate through which the pump light is transmitted, providing both of these improvements. First, the heat removal takes place <u>at the crystal pump face</u>, shortening the conduction path (compared with the ~2 mm dimension in the original design) and reducing the effective thermal impedance. The region of greatest heating directly adjoins the sapphire heat sink. This, the coldest spot in the crystal, is also the region of peak amplification. Second, removing the heat from the pump face (and from no other region) largely eliminates heat conduction from the front to the back of the crystal, creating a zone free of temperature gradients. This gradient-free zone (see below) largely equalizes the optical path length **OPL** $\equiv \int \mathbf{n}\, \mathbf{ds}$ across the aperture of the resonated beam, substantially reducing thermal lensing.

The composite-sample design (Fig. 1) largely resembles the original design (Ref. 7,) since the pump diode array and resonator optics are similar. The pump array is larger (5 bars instead of 4) and less tightly focused, giving a spot 350 μm high and 10 mm long, and the overall pump delivery efficiency is only ~63% because of clipping and non-AR-coated optics. Peak pump power delivered to the crystal is estimated to be 156 Watt. Heat is removed from the 2 mm-thick sapphire plate with water-cooled copper heat sinks containing apertures for pump light delivery.

Two different laser samples[9] were used--$Er_{1.5}Y_{1.5}Al_5O_{12}$ ("Er:YAG") and $Er_3Al_5O_{12}$ ("EAG.") Effective pump absorption coefficients were ~20 $cm^{-1}$ in each case. Brewster-cut faces resulted in sample dimensions of 2mm x 2mm x 10mm x 11.4 mm. The polished laser slabs were "diffusion-bonded" to 10 x 10 x 2 mm sapphire plates in a manner preserving a high-optical-quality interface. Four primary considerations led to selection of sapphire for the plate material: (1) high thermal conductivity (28 W/m •K, to be compared with 5 W/m •K for Er:YAG,) (2) high transparency at the 2.94 μm laser and 965 nm diode pump wavelengths, (3) refractive index difference sufficient for TIR at reasonable angles of incidence ($\Delta n = 0.06$ at 3μm for a 16°

maximum grazing angle,) and (4) ability to bond to Er:YAG. Diffusion bonding of Er:YAG to sapphire,[10] currently developmental, gave bonds best along the midlines of the laser crystals.

Calculated temperature profiles indicate a ~50 °C smaller temperature rise in the pump face/ TIR bounce region for the composite design than in the original design. Whereas the original design shows a steadily-declining temperature due to heat conduction from the front to the back of the crystal, the composite design has a nearly gradient-free region at the back of the crystal.

The utility of the gradient-free zone is illustrated in Figure 2, a conceptual view of the isotherms in a slice through the mid-plane of the laser crystal (assuming uniform heat deposition per unit length and a pump penetration depth short compared with the crystal depth.) The horizontal tilt and focus imposed on a beam entering the crystal at a depth $\mathbf{z_0}$ are respectively proportional to $\partial \mathbf{OPL}/\partial \mathbf{z_0}$ and $\partial^2 \mathbf{OPL}/\partial \mathbf{z_0}^2$, where $\mathbf{OPL} = \int \mathbf{n}\, \mathbf{ds}$. With beam entry and exit via the gradient-free region, these derivatives (and higher-order **z**-axis derivatives) are identically zero, eliminating pump-light-induced horizontal beam steering and focusing.

Figure 3 shows results of thermal lensing measurements performed on the original and composite laser samples, obtained with extra-cavity 633 nm probing (along the path taken by the 2.94 μm beam during laser operation) of the laser crystals experiencing varying diode-array pump powers. As expected, the inverse focal length scales linearly with pump power. Whereas the focal power $(1/f)/P_{pump}$ in the horizontal plane of the original design was -4.9 x $10^{-2}$ $cm^{-1}$/W, the composite design had a focal power of -0.68 x $10^{-2}$ $cm^{-1}$/W, indicating a factor of 7.2 reduction in thermal lensing. The vertical focal power dropped from 3.5 x $10^{-2}$ $cm^{-1}$/W in the original design to 0.81 x $10^{-2}$ $cm^{-1}$/W in the composite design, a factor of 4.2 improvement. These results validate the "gradient - free zone" concept underlying the new laser architecture.

Tests of the EAG composite-sample laser were performed with a cavity length of 27 mm and no intracavity mode-control aperture. Beam-quality ($M^2$) measurements at 300 mW average laser output with a pyroelectric-array camera gave $M_h^2 \approx 1.17$ in the horizontal direction and in the vertical dimension, $M_v^2 \approx 1.44$ was derived. Clearly, even with a short cavity, operation at $(M_h^2 \cdot M_v^2)^{1/2} \sim 1.3$ times diffraction limited is possible for this design. Compared with the original design delivering $P_{out} = 710$ mW at $M_h^2 \approx 3.4$, $M_v^2 \approx 1.4$, with a 40 mm cavity length, the "effective far - field brightness," proportional to $P_{out}/(M_h^2 \cdot M_v^2)$, is comparable. Fig. 3 also shows line-outs of emitted beams of both the composite-sample and original laser (at 48 mm cavity length) operating at ~300 mW output power. While the profiles from the composite laser look nearly gaussian, the original laser design shows spikes, particularly in the horizontal plane (where the lensing is worse.) Although multimode operation cannot be directly blamed on an intracavity lens, it is likely that the original design exhibited higher-order thermal aberrations as well, which would affect beam quality more directly.

Slope-efficiency measurements using the Er:YAG crystal with a pulsewidth and repetition rate of 500 μsec and 120 Hz resulted in a threshold pump power of 1.3 Watt and a maximum average output power of 1.16 Watt. The maximum optical efficiency was 14%, roughly a factor of 2 better than that obtained with the original design. The 18% slope along the nearly-straight mid-portion of the slope-efficiency curve was also an improvement. Further laser performance increases should be obtainable by optimizing the Er concentration, improving the transmission of the pump light, and testing other crystalline host materials with higher luminescence quantum yields.

The new side-pumped, diffusion-bonded laser architecture allows efficient heat removal without flowing cooling water or gas across a crystal face. Its gradient-free region for resonated beam entry and exit provides a degree of thermal-lens compensation reminiscent of a highly-symmetric zig-zag slab system. This advanced sample geometry may be useful in other types of solid-state lasers where the gain is sensitive to operating temperature, or where thermal lensing is especially troublesome.

References
1. R. C. Stoneman and L. Esterowitz, Opt. Lett. **17**, 816 (1992).
2. M. Pollnau, W. Lüthy, H. P. Weber, T. Jensen, G. Huber, A. Cassanho, H. P. Jensen, R. A. McFarlane, Opt. Lett. **21**, 48 (1996).
3. T. Jensen, B. G. Ostroumov, and G. Huber, *OSA Proceedings on Advanced Solid-State Lasers*, Vol. **24**, Bruce H. T. Chai and Steven A. Payne (eds.), 1995, pp. 366 - 370.
4. V. Lupei, S. Georgescu, V. Florea, IEEE J. Quantum Electron. **29**, 426 (1993); M. Pollnau, Th. Graf, J. E. Balmer, W. Lüthy, H. P. Weber, Phys. Rev. A **49**, 3990 (1994).
5. B. J. Dinerman and P. F. Moulton, Opt. Lett. **19**, 1143 (1994).
6. T. Jensen, A. Diening, G. Huber, and B. Chai, in Conference on Lasers and Electro-Optics, OSA Technical Digest Series Vol. **15**, postdeadline paper CPD29 (1995).
7. C. E. Hamilton, R. J. Beach, S. B. Sutton, L. H. Furu, W. F. Krupke, Opt. Lett. **19**, 1627 (1994).
8. J. E. Bernard and A. J. Alcock, Opt. Lett. **18**, 968 (1993).
9. Scientific Materials Corp., 310 Icepond Rd. P. O. Box 786, Bozeman MT 59715.
10. ONYX Optics, 6545 Sierra Lane, Dublin CA 94568.

## Figure Captions

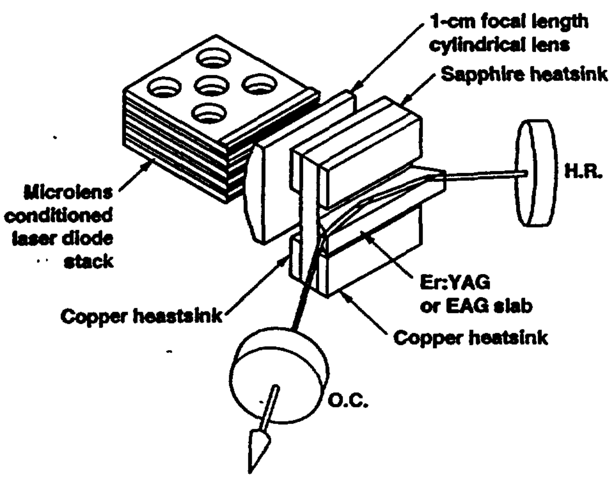


**Figure 1.** Composite-design diode-pumped Er:YAG laser with "TIR-bounce" beam propagation. The Er:YAG slab is diffusion-bonded to a sapphire plate that removes heat directly at the pump face, reducing the gain-region temperature and reducing thermal lensing.

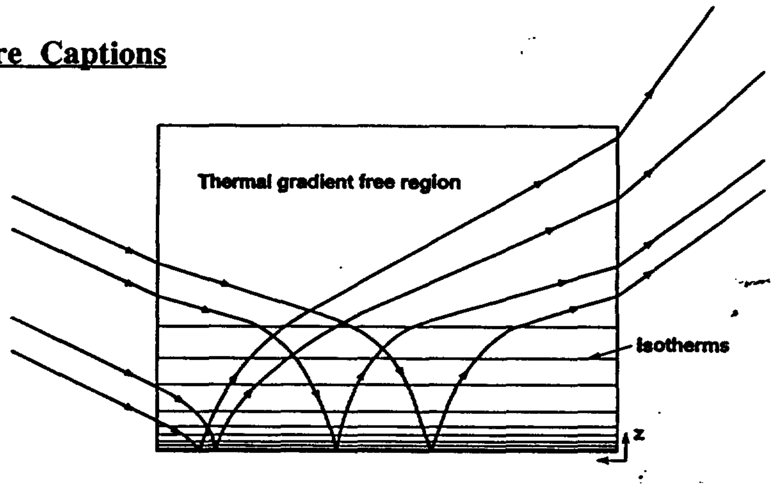


**Figure 2.** Conceptual view of isotherms in a slice through the laser slab's midplane, showing that heat removal at the pump face creates a gradient-free region deep in the crystal. Laser-beam entry and exit via this region eliminates horizontal-axis lensing and beam steering.

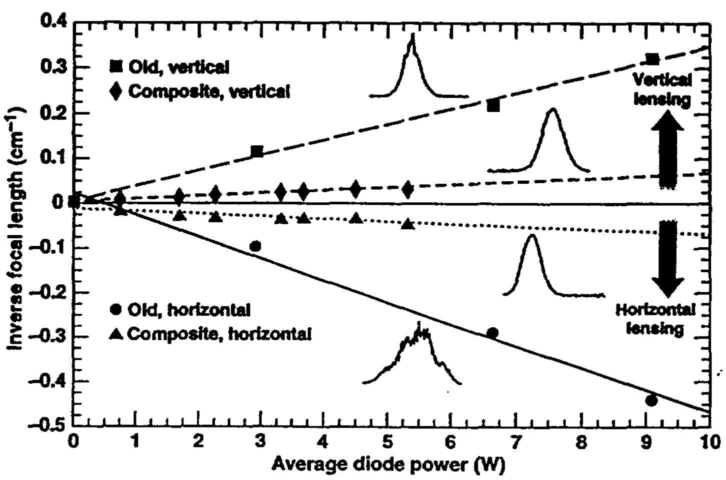


**Figure 3.** Thermal lensing measurements at varying levels of diode pump power, showing greatly-reduced thermal lensing in the composite Er:YAG/sapphire sample. Next to the curves are line-outs of the original and composite laser intensity profiles at 300 mW output power, with no mode-control apertures. The composite laser exhibits a nearly - gaussian mode, but the original laser's mode is aberrated.